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**14. ABSTRACT**

As a result of the work related to and supported by this AFOSR grant I and my collaborators wrote a number of key papers. In particular, we formulated theory of adiabatic dynamics in gapless systems and showed that non-adiabatic effects can be very strong in low dimensional systems. We also related universal non-adiabatic response to fidelity susceptibility and for the first time rigorously showed how universal results similar to Kibble-Zurek scaling emerge from the scaling dimension of the quench operator. Our findings are directly relevant to adiabatic quantum computation and dynamics of cold atoms. We also analyzed situations directly relevant to cold atom physics (like loading bosons into one-dimensional optical lattices) and predicted universal results, which can be measured in current experimental setups.

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# Final report for the proposal:

FA9550-07-1-0038 - (YIP-07)
"DYNAMICS AND THERMODYNAMICS OF MANY-PARTICLE COLD ATOM SYSTEMS"

by Anatoli Polkovnikov,

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During the period of the grant PI and collaborators achieved all the major goals of the proposal. The results of the efforts are published in approximately 20 refereed papers and two book chapters. Also the funding by AFOSR was acknowledged in numerous invited talks, seminars and colloquia (a detailed list of the talks can be found at http://physics.bu.edu/~asp/talks.htm). A particular correspondence between different topics of the proposal and the publications is given below (in few occasions where one publication is relevant to two topics it is mentioned twice)

1. **Analysis of the phase diagram of disordered 1D bosons**:

   - E. Altman, Y. Kafri, A. Polkovnikov and G. Refael, "The insulating phases and superfluid-insulator transition of disordered boson chains", Phys. Rev. Lett. **100**, 170402 (2008)

   - Ehud Altman, Yariv Kafri, Anatoli Polkovnikov, Gil Refael, "Superfluid-insulator transition of disordered bosons in one-dimension" , Phys. Rev. B **81**, 174528 (2010).

2. **Studying time evolution of atomic systems after a quench and analysis of the Kibble Zurek mechanism:**

   - V. Gritsev, E. Demler, M. Lukin, and A. Polkovnikov, "Analysis of quench dynamics of coupled one dimensional condensates using quantum sine Gordon model", Phys. Rev. Lett. **99**, 200404 (2007).

   - V. Gritsev, E. Demler, M. Lukin, and A. Polkovnikov, "Analysis of quench dynamics of coupled one dimensional condensates using quantum sine Gordon model", Phys. Rev. Lett. **99**, 200404 (2007).

   - L. Mathey, A. Polkovnikov, A.H. Castro Neto, "Phase-locking transition of coupled low-dimensional superfluids", Europhys. Lett. **81**, 10008 (2008).

   - L. Mathey, A. Polkovnikov, "A supercritical superfluid and vortex unbinding following a quantum quench", Phys. Rev. A 80, 041601(R) (2009),

   - L. Mathey, A. Polkovnikov**,** Light cone dynamics and reverse Kibble-Zurek mechanism in two-dimensional superfluids following a quantum quench, Phys. Rev. A **81**, 033605 (2010)

   - C. De Grandi, V. Gritsev, A. Polkovnikov, "Quench dynamics near a quantum critical point", Phys. Rev. B **81**, 012303 (2010)

   - C. De Grandi, V. Gritsev, A. Polkovnikov, "Quench dynamics near a quantum critical point: application to the sine-Gordon model", Phys. Rev. B **81**, 224301 (2010).

   - R. Hipolito, A. Polkovnikov, "Breakdown of macroscopic quantum self-trapping in coupled mesoscopic one dimensional Bose gases", Phys. Rev. A **81**, 013621 (2010)

3. **Decay of superfluid currents in low dimensional systems**.

   - Ippei Danshita, Anatoli Polkovnikov, "Accurate numerical verification of the instanton method for macroscopic quantum tunneling: dynamics of phase slips", *arXiv:0908.2592*, accepted to Phys. Rev. B.

4. **Understanding slow dynamics in isolated systems (additional goal added in the end of first year) with applications to cold atom experiments**

   - A. Polkovnikov and V. Gritsev, "Breakdown of the adiabatic limit in low dimensional gapless systems", Nature Physics **4**, 477 (2008).

   - R. Barankov, A. Polkovnikov, "Optimal non-linear passage through a quantum critical point", Phys. Rev. Lett. **101**, 076801 (2008).

   - C. De Grandi, R. Barankov, A. Polkovnikov, "Adiabatic nonlinear probes of one-dimensional Bose gases", Phys. Rev. Lett. **101**, 230402 (2008).

   - A. Altland, V. Gurarie, T. Kriecherbauer, and A. Polkovnikov, "Non-adiabacity and large flucutations in a many particle Landau Zener problem", Phys. Rev. A **79**, 042703 (2009).

   - C. De Grandi, A. Polkovnikov, "Adiabatic perturbation theory: from Landau-Zener problem to quenching through a quantum critical point", *arXiv:0910.2236*, contribution to "Quantum Quenching, Annealing and Computation", Eds. A. Das, A. Chandra and B. K. Chakrabarti, Lect. Notes in Phys., vol. 802 (Springer, Heidelberg 2010

   - Vladimir Gritsev, Anatoli Polkovnikov, "Universal Dynamics Near Quantum Critical Points", *arXiv:0910.3692,* Contribution to the book "Understanding Quantum Phase Transitions", edited by Lincoln Carr (Taylor & Francis, Boca Raton, 2010)

5. **Thermodynamic properties of many-body systems driven from equilibrium**

   - A. Polkovnikov, "Microscopic diagonal entropy and its connection to basic thermodynamic relations", *arXiv:0806.2862*.

   - A. Polkovnikov, "Microscopic expression for the heat in the adiabatic basis", Phys. Rev. Lett. **101**, 220402 (2008)

6. **Using interference for probing correlated fermionic states in cold atoms. Analyzing shot noise in the interference experiments.**

   - A. Polkovnikov, "Shot noise of interference between independent atomic systems", Europhys. Lett. **78**, 10006 (2007).

   - V. Gritsev, E. Demler, A. Polkovnikov, "Interferometric probes of paired states", Phys. Rev. A 78, 063624 (2008).

7. **Developing new theoretical approaches for quantum dynamics near the classical limit**

   - A. Polkovnikov and V. Gritsev, "Breakdown of the adiabatic limit in low dimensional gapless systems", Nature Physics **4**, 477 (2008).

   - A. Altland, V. Gurarie, T. Kriecherbauer, and A. Polkovnikov, "Non-adiabacity and large flucutations in a many particle Landau Zener problem", Phys. Rev. A **79**, 042703 (2009).

   - B. Berg, L. I. Plimak, A. Polkovnikov, M. K. Olsen, M. Fleischhauer, W. P. Schleich, "Commuting Heisenberg operators as the quantum response problem: Time-normal averages in the truncated Wigner representation", Phys. Rev. A **80**, 033624 (2009)

   - A. Polkovnikov, "Phase space representation of quantum dynamics", **Annals of Phys. 325,** 1790 (2010)**.**

As a result of the work related to and supported by this AFOSR grant I and my collaborators wrote a number of key papers. In particular, we formulated theory of adiabatic dynamics in gapless systems and showed that non-adiabatic effects can be very strong in low dimensional systems. We also related universal non-adiabatic response to fidelity susceptibility and for the first time rigorously showed how universal results similar to Kibble-Zurek scaling emerge from the scaling dimension of the quench operator. Our findings are directly relevant to adiabatic quantum computation and dynamics of cold atoms. We also analyzed situations directly relevant to cold atom physics (like loading bosons into one-dimensional optical lattices) and predicted universal results, which can be measured in current experimental setups.

Another major effort related to the proposal was developing phase space methods for quantum dynamics and applying these methods to cold atom systems. The summary of these developments were just published in a review paper in Annals of Physics (see Ref. above). There I established a complete perturbative in quantum fluctuations representation of quantum dynamics in a phase space (i.e. without wave function or density matrix). I filled the gaps which existed in the previous literature (starting since early days of quantum mechanics) like defining non-equal time correlation functions and finding quantum corrections (to the truncated Wigner approximation) through quantum jumps. I also extended the formalism to spin systems. Using this formalism it was possible to analyze many non-equilibrium problems directly related to cold atoms. In particular, many-body generalization of the Landau-Zener problem, directly related to the physics of BCS-BEC crossover (A. Altland, V. Gurarie, T. Kriecherbauer, and A. Polkovnikov, Phys. Rev. A **79**, 042703 (2009).); Thermalization of two-dimensional superfluids following a quantum quench (L. Mathey, A. Polkovnikov, Phys. Rev. A 80, 041601(R) (2009), Phys. Rev. A **81**, 033605 (2010)) and breakdown of macroscopic self-trapping in coupled one-dimension Bose gases (R. Hipolito, A. Polkovnikov, Phys. Rev. A **81**, 013621 (2010)). Two additional projects involving other practical applications of these methods are currently in final stages and should be posted on the arXiv soon.

Other results of my work include understanding phase diagram of strongly disordered bosons in one-dimension, verification of the instanton method to the decay of superfluid current in one-dimensional optical lattices, understanding of shot noise (which is different in nature from the Hanbury-Brown-Twiss effect and noise correlations) on the time of flight experiments in cold atoms, and understanding quench dynamics in low-dimensional models related to cold atoms (like sine-Gordon model).

The work on the project also lead to new insights and stimulated new ideas some of which are reflected in the new proposal funded by the AFOSR under the same title.

Through this project I supported the following personnel two graduate students: Claudia De Grandi and Rafael Hipolito, and one Post-Doc: Roman Barankov. They all contributed to publications acknowledging support by this grant.

In summary I would like to thank the AFOSR for providing this funding opportunity for me. I believe that cold atoms opened new venues for exploring non-equilibrium quantum dynamics. It is likely that future technologies will strongly rely on coherent manipulations in quantum systems and thus understanding of both fundamental and applied aspects of quantum dynamics away from equilibrium becomes a problem of primary importance.